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The Hydraulic-Machinery Laboratory at the California Institute of Technology

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This paper gives a description of the arrangement, equipment, and instrumentation of the hydraulic-machinery laboratory at the California Institute of Technology. This laboratory was designed essentially to work with problems involving high heads, high speeds, and moderately large powers and rates of flow. The instruments and equipment permit both speed and precision in testing, an overall accuracy of 0.1 per cent being attainable. For the past two years the laboratory has been used for the study of pumping problems of the Colorado River aqueduct, a project which will have pumps totaling 350,000 hp when completed.

THE Hydraulic-Machinery Laboratory is a joint enterprise of the California Institute of Technology and the Metropolitan Water District of Southern California. In November, 1933, the formation of the laboratory was authorized by F. E. Weymouth, general manager and chief engineer of the Metropolitan Water District, a three-year agreement was signed by the two organizations, and the design of the laboratory was begun. Construction was completed by the end of August, 1934, and since that time this laboratory has been in continuous operation.

The need for the laboratory arose principally from the extraordinarily severe problems that faced the District engineers in connection with the pumping plants for the Colorado River aqueduct. This aqueduct will have a capacity of 1600 cfs, and in bringing this water the 300 miles from the Colorado River to Los Angeles and the other Southern California municipalities which have united to form the Metropolitan Water District, it is necessary to lift it a total of nearly 1700 ft. To do this will require about 350,000 hp, which classes it as the largest pumping project in existence. The location finally selected divides this lift between five pumping stations, working against average heads of from 146 ft for the lowest to 444 ft for the highest. Very little precedent was available for plants of such size, to assist the engineers of the District in answering questions concerning maximum permissible head per stage, single- or double-suction pumps, optimum speeds, attainable efficiencies, and desirable operating characteristics. It was felt that a properly equipped laboratory would be of great assistance in studying such problems, and would amply justify the expense required, both by savings expected and by the insurance of obtaining the most satisfactory type of equipment.

The responsibility of supervising the design, construction, and operation of the laboratory was placed in the hands of a group consisting of Professors Th. von Kármán, R. L. Daugherty, and R. T. Knapp for the Institute, and J. M. Gaylord, chief electrical engineer, and R. M. Peabody, senior mechanical engineer, for the district. In the two years since the construction was completed, the laboratory has been engaged in working on the following problems:

1 A comprehensive study of a group of pumps of varying specific speeds and other operating characteristics for the purpose of selecting the proper specifications for the pumps in the different stations.

2 Precision acceptance tests of both bidders' and contractors' model pumps.

3 A study of the transient flow characteristics of the contractors' model pumps in order to ascertain their behavior during emergency conditions such as power failure and shaft breakage.

4 Special internal surveys of the hydraulic conditions existing within the case, as they affect either structural design or operating efficiency of the unit.

5 Study of control-valve characteristics throughout the operating range from closed to full open.

6 Metering investigations.

The purpose of this paper, however, is not to discuss any of the details of the work of the laboratory, but is rather to give a description of the laboratory itself, its equipment and instrumentation, and thus furnish a foundation for subsequent reports dealing with the various investigations that have been undertaken.

General Description of Laboratory Circuits

(*A*) *Main Circuit.* The equipment in the laboratory is arranged in a series of closed hydraulic circuits, to increase its convenience and usefulness. The main circuit is shown in Fig. 1 and consists essentially of the low-pressure regulating tank, the machine under test connected to the dynamometer, the venturi meters, and the high-pressure service pumps. This circuit can be utilized with flow in either direction through the test machine, for by means of interconnections the suction and discharge connections of the service pumps may be reversed. Also, parts of the circuit not needed can be by-passed. An example of this is shown in Fig. 2, which is the circuit most used for the normal pump tests.

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(*B*) *Pressure-Regulating Circuit.* Superimposed on the main circuit are two auxiliary closed circuits, the arrangements of which can be seen in Fig. 3. The pressure-regulating circuit has a flow of about 450 gpm. Its function is to regulate the pressure in the low-pressure tank to any desired value between about 120 ft above atmospheric and 20 ft below. Since the only connection between the main circuit and the atmosphere is through this auxiliary circuit, it serves to stabilize the pressure level of the main circuit at the point desired. As the rate of flow through this regulating circuit is constant, the pressure in the tank is controlled by varying the resistance offered by the by-pass valve shown in Fig. 3. This valve is actuated from the operator's table. If the pressure desired is below atmosphere, it is necessary to run the by-pass pump to eject the regulating flow from the tank. In this case the vacuum pump located above the tank is also run to remove any dissolved air that comes out of solution in this region of low pressure. Since this pump operates through a barometric loop, no water leaves the system by way of this path.

(*C*) *Cooling Circuit.* The second auxiliary circuit shown in Fig. 3 is the cooling circuit. Fundamentally, all of the energy supplied to the machines in the main circuit is dissipated in heating the water. In some conditions of operation the dynamometer may be contributing 450 hp, the two high-pressure ser-

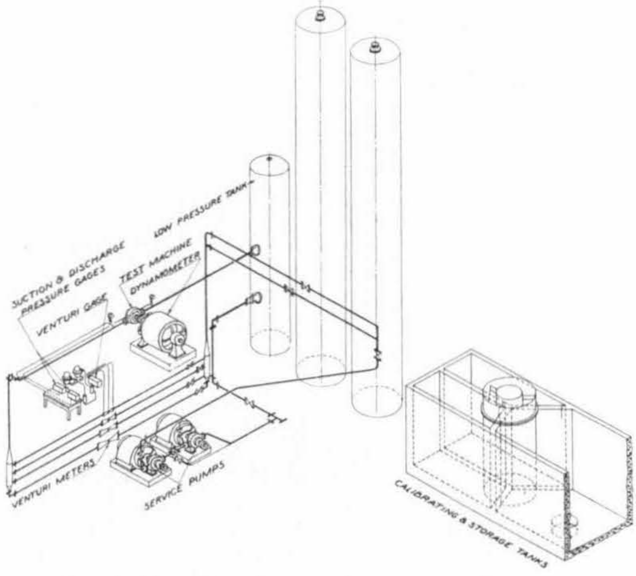

FIG. 1 THE MAIN CIRCUIT OF THE LABORATORY

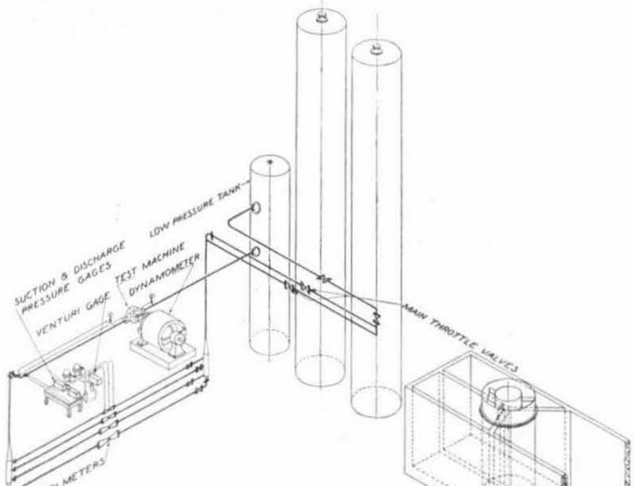

FIG. 2 CIRCUIT USED FOR NORMAL PUMP TESTS

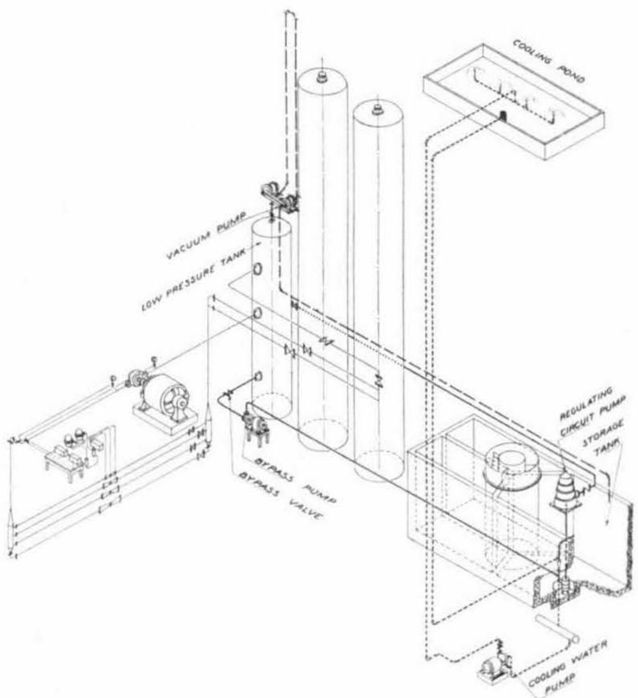

FIG. 3 ARRANGEMENT OF AUXILIARY CLOSED CIRCUITS SUPERIMPOSED ON THE MAIN CIRCUIT

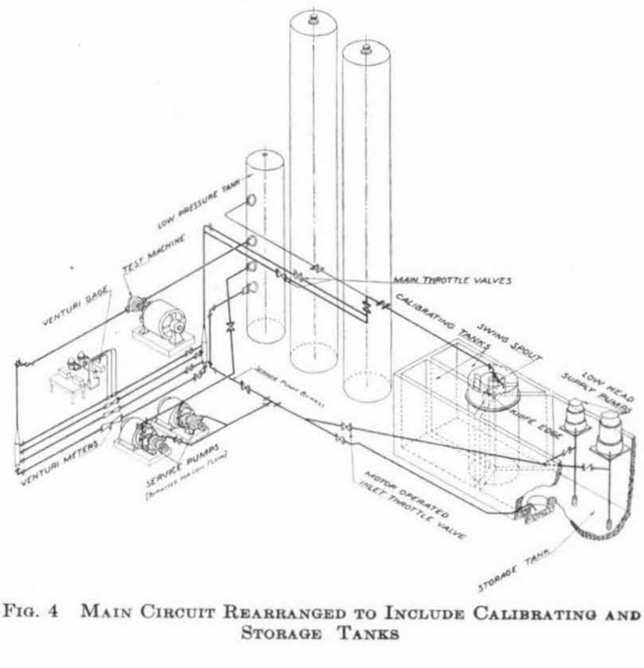

FIG. 4 MAIN CIRCUIT REARRANGED TO INCLUDE CALIBRATING AND STORAGE TANKS

vice pumps 250 hp each, and other sources say another 100 hp. The main circuit contains something less than 400 cu ft of water. Therefore, if nothing were done to control it, the temperature would rise about 2 deg per min. Since such a state would be intolerable, a portion of the flow coming out of the low-pressure tank through the by-pass line is diverted to a pump which sends it to spray nozzles in a pond on the roof. In this way enough heat is dissipated to keep the temperature under control for all conditions of operation.

(*D*) *Calibrating Circuit.* For the purpose of calibrating the venturi meters, or for making a direct volumetric determination of given points of operation of the machine under test, it is desirable to rearrange the main circuit as shown in Fig. 4 to include the calibrating and storage tanks. It should be noted that the venturi meters employed are of symmetrical construction so that they can measure flow in either direction. Although Fig. 4 shows the circuit arranged to calibrate one direction of flow, it is possible to reverse the flow through the meters without

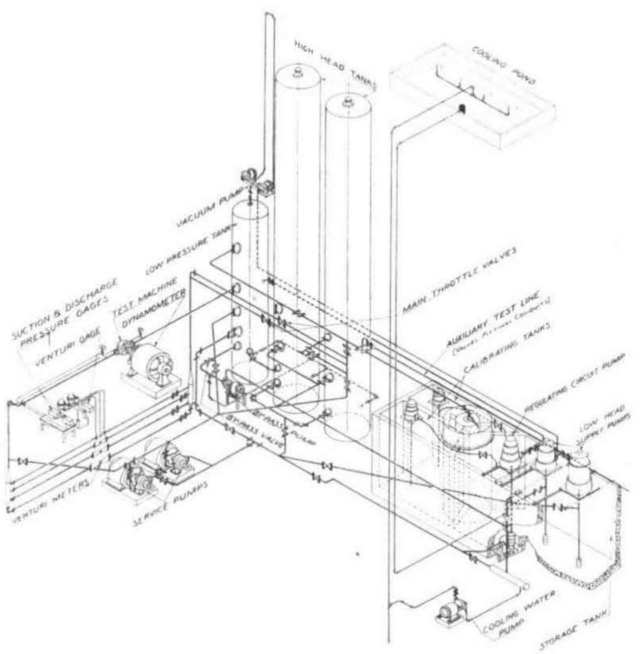

FIG. 5 COMPLETE PIPING DIAGRAM OF THE LABORATORY

changing the arrangement for calibration. Thus, the meters may be calibrated in place under all possible operating conditions.

(*E*) *Special Circuits.* Although the arrangements previously described are the ones used for the majority of the work, other circuit combinations are easily obtained. Fig. 5 shows the complete piping diagram for the laboratory, and may serve to demonstrate the versatility of the system.

GENERAL INSTALLATION

The main units of the laboratory equipment are housed in a room about 20 ft wide, 48 ft long, and 50 ft high. A working floor was constructed about 12 ft above the original level. The general appearance of this part of the laboratory is shown in Figs. 6 and 7. The basement formed below this floor houses the high-pressure service pumps, the by-pass valve and pumps, the venturi meters and other auxiliary apparatus. The calibrating tanks, storage tank, and supply pumps are in a long room that opens off from the northeast corner of the working floor. Thus, it will be seen that the entire installation is very compact and convenient to operate.

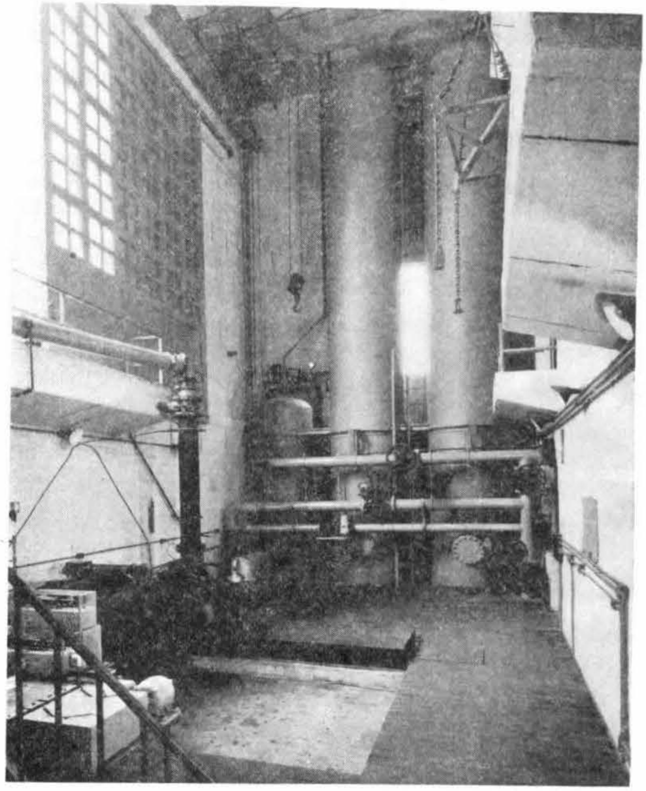

FIG. 6 WORKING FLOOR LOOKING NORTH, SHOWING PRESSURE TANKS IN THE BACKGROUND

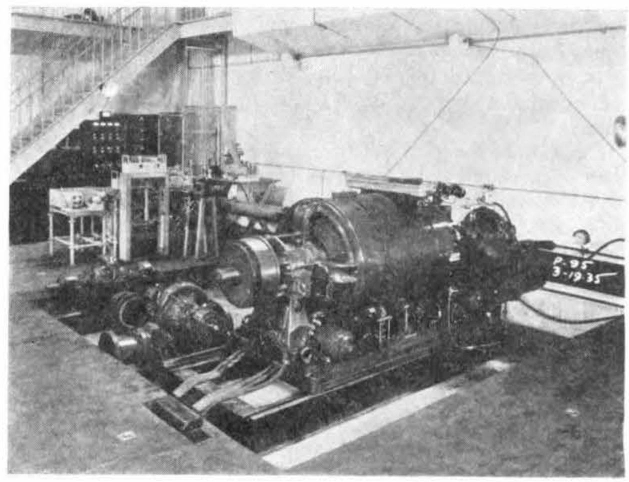

FIG. 7 WORKING FLOOR LOOKING SOUTH, SHOWING DYNAMOMETER IN THE FOREGROUND

LABORATORY EQUIPMENT

(*A*) *Dynamometer.* The dynamometer was furnished by the General Electric Company under special specifications prepared by the laboratory. It has a rated output of 275 hp as a motor, with ample overload capacity in reserve. In fact, it has delivered as much as 500 hp for short periods during the testing program. As a generator, its rating is correspondingly slightly higher. It can operate at speeds up to 5000 rpm, and has been tested to a runaway speed of 5500 rpm. It is, of course, a direct-current machine and has a 250-v. normal operating rating. The separately excited fields are wound for 125 v. It may be operated equally satisfactorily in either direction of rotation.

The armature is provided with special high-speed ball bearings to eliminate the slight shift in radial position of the armature with respect to the frame which would have been present if sleeve bearings had been used. This shift would have been objectionable, since the variable unbalance accompanying it would have been considerably greater than the limits of accuracy of the torque measurements desired.

To provide the means for measuring the dynamometer torque, the frame is mounted on spherical roller bearings placed over

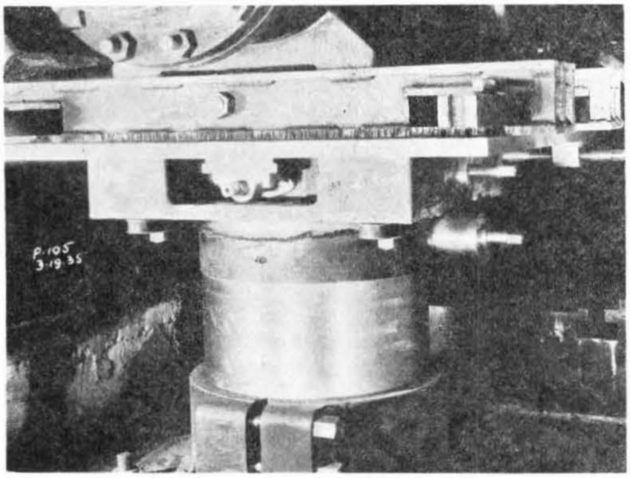

Fig. 8 Adjustable Base for Mounting Test Units

the shaft bearing housing. The outer races of these bearings in turn are mounted in sleeve bearings and are rotated slowly (about 7 rpm) in opposite directions by individual 0.5-hp motors. Thus, the static friction of these bearings is eliminated and the running friction is neutralized by balancing them against each other.

In addition, the possibility of these bearings "Brinelling" is eliminated, thus insuring the maintenance of the original sensitivity of the mounting to changes in torque. The frame is prevented from rotating by two stops fastened to the base. These are so adjusted that the dynamometer is free to rotate a total of only a few thousandths of an inch. No clamp is provided for use when starting or stopping, as it is unnecessary when the frame rotation is so limited.

A 5-kw, two-pole alternator is mounted on a shaft extension at one end of the dynamometer. The frame of this machine is fastened to the main-dynamometer frame; therefore, it has no effect on the torque reading of the dynamometer under any circumstances. The power from this alternator can be used to drive synchronous motors in any part of the laboratory which will therefore run either with the identical speed of the dynamometer, or at some definite fraction of that speed, as determined by the number of poles on the motor. One such motor is used to drive the tachometer and a contactor for giving a signal every 5, 10, or 50 revolutions of the dynamometer shaft.

The bottom and sides of the dynamometer base are carefully machined to fit the ways of two sub-bases. These are mounted on a massive concrete structure which is independent of the rest of the laboratory, this being done to reduce vibration to a minimum. One sub-base is mounted for use with machines having an axial pipe connection, such as single-suction pumps or axial-discharge turbines. The other sub-base is mounted at right angles to this position, for use with machines having both pipe connections at right angles to the shaft, such as double-suction pumps. The ways of the sub-bases provide for considerable axial adjustment in the position of the dynamometer, to meet the variations in dimensions of the different machines to be tested. The dynamometer is moved from one sub-base to the other by means of a traveling crane. The special bridle which has been constructed to facilitate this change may be seen on the right-hand wall in Fig. 6. The general appearance of the dynamometer is shown in the foreground in Fig. 7, while the two sub-bases may be seen in Fig. 6.

Since both the speed and the power involved are rather high, it has been thought advisable to provide a convenient emergency stop. Therefore, a system of overhead wires connected to a master relay switch is strung around the laboratory, so that in case any trouble develops the dynamometer can be shut down from any point on the operating floor.

The power supply for the operation of the dynamometer comes from a 700-kw motor-generator set which is part of the wind-tunnel equipment housed in the same building. Since it is not

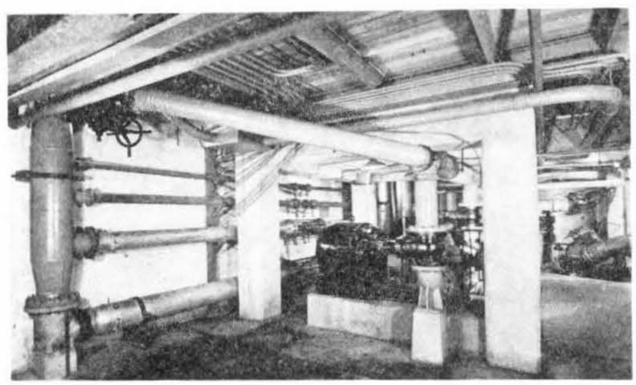

Fig. 9 General View of Laboratory Basement Showing High-Head Service Pump

properly a part of this laboratory, no further description of it will be given here.

(*B*) *Adjustable Testing Base.* Installed on the same concrete platform with the dynamometer is an adjustable testing base on which the different machines under test are mounted. The principal adjustment provided is in the vertical direction, since there is considerable variation in the distance between the shaft and the base plate on the different machines submitted for test. Convenient adjustments of small range are also provided in the two horizontal directions and also in rotation. These latter movements greatly facilitate the precise lining-up of the machine to be tested with the dynamometer. A view of this base and the adjusting screws is seen in Fig. 8. The time required to change machines is reduced considerably by the use of this base, even though exact alignments must always be secured, due to the high speeds of rotation and powers involved.

(*C*) *Low- and High-Head Tanks.* The low-head tank and the two high-head tanks shown in Figs. 1 to 5, inclusive, are all of similar construction. They comply with the A.S.M.E. Unfired Pressure Vessel Code, Class I specifications, and are electrically welded, stress relieved, and all seams were X-rayed. In addition they were tested hydrostatically to 500 lb per sq in., although they are rated at 300 lb per sq in. working pressure. Their general appearance is shown in Fig. 6, although it must be remembered that they extend down to the floor below, making them about 12 ft longer than they appear in the illustration. The low-head tank has a volumetric capacity of about 350 cu ft, while the high-head tanks each have a capacity of about 1000 cu ft.

(*D*) *Calibrating and Storage Tanks.* Two open calibrating tanks and a storage tank are provided. They are all 10 ft in depth and are built into a 10 × 10-ft concrete channel which was in the original building. In order to eliminate leakage, these tanks are lined with $^1/_8$-in. steel, welded in place and grouted to the original walls. The sides are vertical. The two calibrating tanks have capacities of 300 and 1000 cu ft, respectively, while the storage tank has a capacity of about 5000 cu ft. They are all provided with broad crested overflow wiers to prevent danger of damage to the rest of the laboratory and adjoining electrical equipment.

(*E*) *High-Head Service Pumps.* The two service pumps shown in the main circuit are located in the basement. They furnish the high-head water supply needed for reverse-flow tests, turbine tests, etc. They are single-stage, double-suction pumps and have normal ratings of 360 ft head and 2400 gpm. They are driven by 200-hp induction motors at a speed of 2900 rpm. They are installed on the foundation of the isolated dynamometer

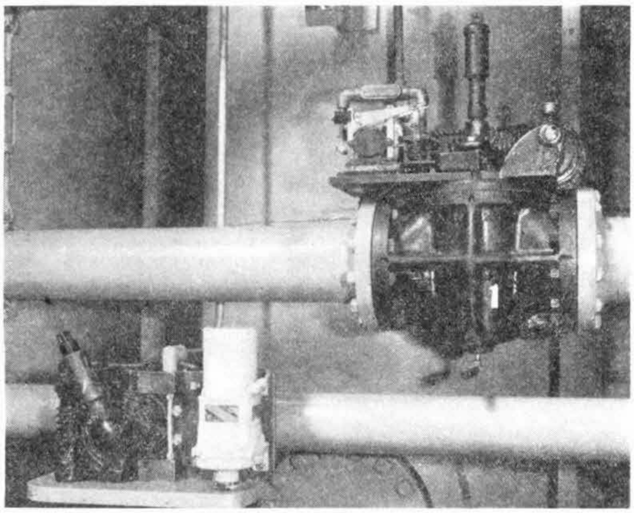

Fig. 10 Motor-Operated Throttle Valves Remotely Controlled From the Operator's Table

structure, as shown in Fig. 9. It is evident from the piping diagram shown in Fig. 5, that they can be operated either in series or in parallel, and that there are a number of alternate paths both for the suction and the discharge.

(*F*) *Low-Head Supply Pumps.* Two short-column deep-well pumps are submerged in the storage tank. Both develop heads of 50 ft and are arranged to operate either singly or in parallel. The smaller one has a capacity of 4 cfs while the larger has a capacity of 8 cfs. They are used to supply the intake head when a test pump is discharging to the calibrating tanks, to feed the service pumps when they are operating in parallel, or for other purposes where a relatively large quantity of water at low head is needed.

(*G*) *Auxiliary Pumps.* The supply and by-pass pumps of the regulating circuit are matched as to capacity, since they operate in series. They have ratings of 120 and 30 ft head, respectively, both at 450 gpm. The supply pump is of the four-stage short-column deep-well type and is submerged in the storage tank. The by-pass pump is of the simple single-suction close-built type with integral driving motor. Of its 30 ft total head, 20 ft or more at times may be suction-lift. Both these and all the other auxiliary pumps are induction-motor driven.

The calibrating-tank pumps are used to empty these tanks after a calibrating run has been made. It was felt undesirable to have any openings in these tanks because of possible leaks. Therefore, these pumps are again simply short-column deep-well types which are suspended from above and discharge over the tops of the side walls of the calibrating tanks. Incidentally, the one in the larger tank has an adjustable-pitch propeller which gives the possibility of carrying on some interesting work with it in the future. With its present setting, it has a capacity of about 5000 gpm against a 12-ft head.

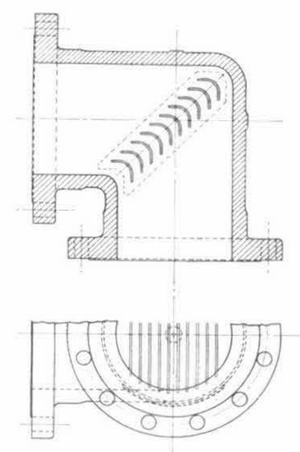

Fig. 11 Section Through the Cast-Iron Vane Elbow

The cooling-water pump is of the simple single-stage type and has a capacity of 150 gpm against a head of 120 ft. The vacuum pump is a Nash Hytor, and can be seen mounted above the low-pressure tank in Fig. 6.

(*H*) *Valves.* For convenience, it was decided to operate several of the valves by motor, and to control them remotely from the operator's table. Grease-lubricated plug cocks were utilized for this purpose, with special diamond ports for the main throttle valve and the by-pass valve. The normal positive stops were removed, limit switches installed in their places, and a 0.25-hp motor with integral gear reducer and electric brake was connected by chain to the hand-wheel shaft of the valve mechanism. Fig. 10 shows the two throttle valves in position.

Grease-lubricated and sealed plug valves were also used on the bank of venturi meters, because they were apparently the most leak-proof under operating conditions and it was very necessary that there should be no leakage flow through the meter lines not being used. However, these valves are manually operated since they are used only when changing meters.

Gate valves were used in the remainder of the piping system. Of these, some were in key positions where leakage through a closed valve would affect the accuracy of the measurements, while others were so placed that leakage was of small moment. For the key positions double-disk valves were employed, with special bleeder connections between the disks. No leakage from an open bleeder on a closed valve is positive assurance that there is no leakage through the valve.

(*I*) *Vane Elbows.* In several locations in the laboratory piping system it was desirable to have as little disturbance as possible downstream from an elbow. For this purpose a series of vane elbows were designed by the laboratory, patterned after wind-tunnel practice. Two types were constructed, one a cast-iron casing with steel vanes placed in the core, and the other of all-welded construction. Fig. 11 is a section through a cast elbow, showing the vane spacing which is typical for all sizes. The cast type was made in the 10-in. size only, while the welded construction was employed for 8-, 12-, and 16-in. sizes. Figs. 12 and 13 show the appearance of the finished elbows. It should be noted that it is possible to secure a most compact construction with the vane-type elbow.

Laboratory Instrumentation

Before the instruments were designed, a thorough study of the needs of the laboratory was made. This resulted in the following general specifications for the entire group of instruments:

1 Precision and sensitivity. The work contemplated called for an accuracy of an individual reading of 0.1 per cent.

2 Elimination of personal equation. The necessity of using several different operators made it desirable to have the readings as impersonal as possible.

3 Primary standard type of instruments. Part of the work contemplated for the laboratory was the testing of model pumps,

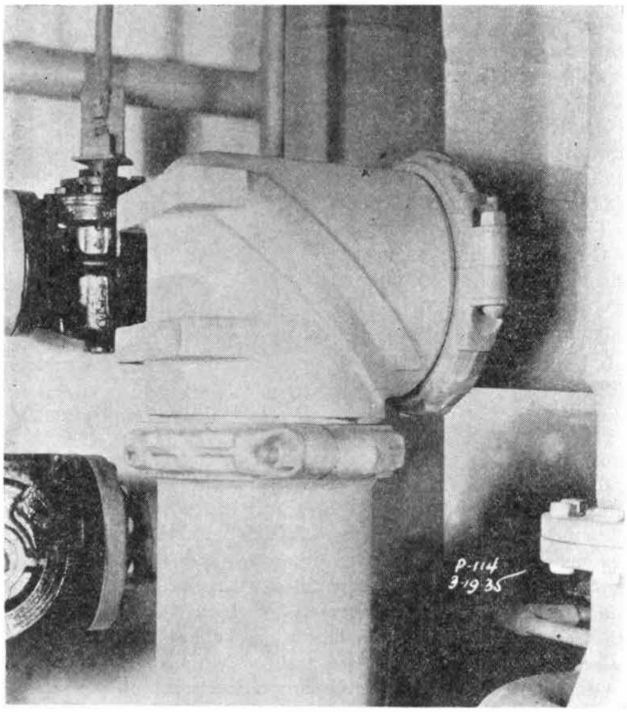

FIG. 12 THE 10-IN. CAST-IRON VANE ELBOW

supplied by different bidders or contractors. Due to the variety of interests involved, it was felt that instruments whose accuracy depended on fundamental measurements of length, weight, and time were to be preferred, where possible, to those of the secondary standard type whose accuracy depended entirely on calibration.

4 Speed of measurement. It was known in the beginning that there was a great deal of work to be done by the laboratory in the limited time available, therefore an instrument ensemble which could speed up the observations without sacrificing accuracy would be very advantageous.

5 Flexibility. Although certain tasks were definite at the start, the entire program could not be outlined ahead of time, because the project was fundamentally a research undertaking. For this reason it was decided to strive for as much versatility as compatible with the known objectives of the laboratory.

Quantities to Be Measured or Controlled. The fundamental quantities for which instruments were to be designed to measure or control were speed, torque, inlet and discharge pressures, and rate of flow. During the course of the work other instruments were developed to measure special properties, but they do not properly belong to the primary equipment of the laboratory and will not be described here.

Speed. In working with high-speed hydraulic machinery, probably the measurement and control of speed causes the most difficulty. Not only is it hard to measure in itself, but the slight variations present with most equipment are reflected in the torque, head, and flow readings as well. Therefore, it was decided to endeavor to construct a speed-control system to hold the test machine at the precise speed at which the tests were desired, independent of fluctuations of load or other disturbances. The basic principle finally adopted is a comparison between a known standard speed and the speed of the machine under test, with any existing difference, no matter how small, acting to correct the speed of the test machine.

Standard Reference Speed. The primary accuracy of such a system depends first upon the accuracy of the reference speed. The first thought for a source of such a reference is naturally a synchronous motor driven from the local power supply. The accuracy of this source over long periods of time is unquestioned, since it is used to drive clocks which are never out more than a total of a few seconds in 24 hr, which is a precision much greater than the 0.1 per cent set for the laboratory instruments. However, a more careful investigation showed that the situation was not so favorable. Short-time variations of 0.75 per cent were found to be relatively common, lasting for periods of from a few seconds to several minutes. Since this condition was not tolerable, it was decided to construct a 1-kw standard-frequency system, the power of which could be used to drive the standard reference motor, a chronograph, and other auxiliaries which might demand an absolutely constant, known speed.

For the basis of this system a 40-kilocycle quartz crystal was chosen, provided with a thermostatic case. This frequency is

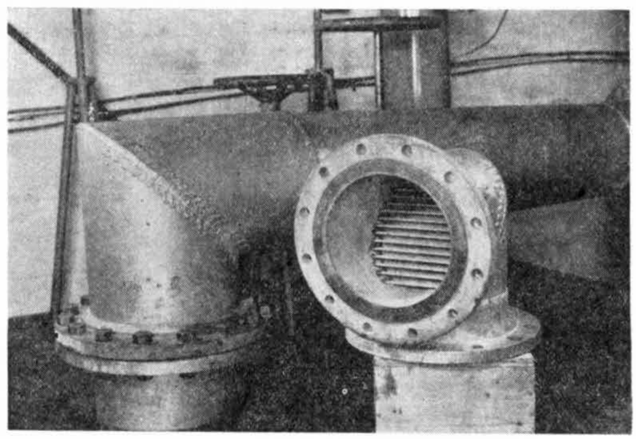

FIG. 13 THE 12-IN. WELDED VANE ELBOW

picked up in the usual manner with a loosely coupled vacuum-tube circuit and then stepped down to 800 cycles through a pair of multivibrators acting in series. This is then amplified until a few watts of power are available and a special 800-cycle synchronous motor is driven by it. This in turn operates a 50-cycle commutator which is used to control a thyratron inverter circuit. The output from this is 1 kw of 50-cycle single-phase power at 110 v.

There are two simple checks of the accuracy of this system. In the first, the frequency of the quartz crystal is compared with the carrier frequency of one of the several local radio stations. This carrier frequency is claimed to be accurate and constant to one part in three hundred thousand. A convenient little circuit employing one of the small cathode-ray tubes, now so popular for silent tuning of radios, serves to visually indicate the beats between the two systems. By this means it has been determined that the laboratory standard-frequency system has a minimum accuracy of one part in one hundred thousand. The second check is a rough one and is used primarily to insure that the multivibrators are operating on the proper steps. It consists in simply comparing the 50-cycle output frequency from the inverter

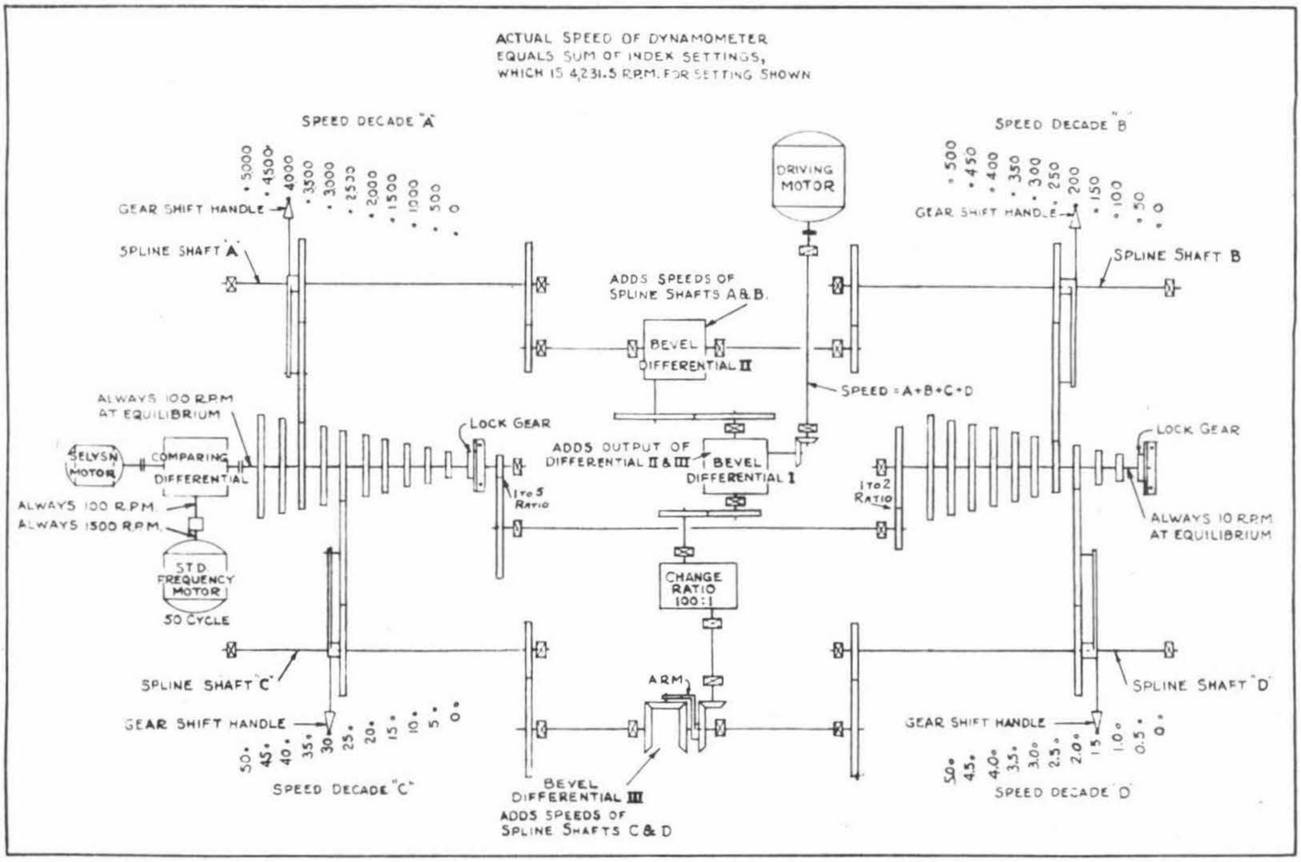

Fig. 15 Diagram of Gearbox Internal Arrangement

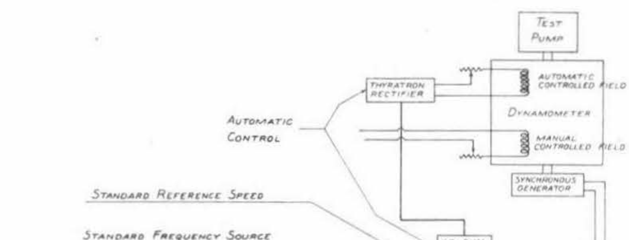

Fig. 14 The Dynamometer Speed-Control System

with the local 50-cycle power line. Incidentally, this gives a constant check on the deviations of the local power and has shown that the laboratory was amply justified in constructing its own standard-frequency system.

Dynamometer Speed Control. The speed-control system, shown in Fig. 14, is built around two synchronous motors, one operated by the standard-frequency system and the other by the alternator on the dynamometer shaft. These drive two shafts of a small bevel-gear differential. The third shaft therefore turns at a speed proportional to the difference of the other two. This shaft actuates a phase shifter (in this case a selsyn motor driven through a friction clutch and limited in motion by stops) which controls the output of a battery of thyratron rectifiers. These furnish the excitation field for the shunt-wound dynamometer, and thus control its speed. It will be seen that any difference in speed between the dynamometer and the speed standard acts immediately to correct itself. The only position of equilibrium is absolute synchronism of the two systems.

One detail of the field control is of interest. The field windings on each pole are split into two equal coils, thus giving two equal field circuits. Only one of these receives its excitation from the controlled thyratron rectifiers. The other goes to the normal direct-current laboratory exciter bus. By means of field rheostats, the relative strengths of the fixed and variable portions of the field windings are adjusted easily to eliminate any tendency for hunting to occur.

Interposed between the control differential and the dynamometer-driven synchronous motor is a multirange gearbox. With this it is possible to adjust the ratio between the standard reference speed and that of the dynamometer so that the latter may be operated at any speed between 1000 and 5000 rpm in one-half revolution steps. This is accomplished with four gear-shift levers by use of differentials which permit the addition of ratios rather than simple multiplication.

Fig. 15 is a line diagram of the internal arrangement of the gearbox. With this construction each shift handle controls a decade, the steps of which are 500, 50, 5, and 0.5 rpm, respectively, which makes the setting of any chosen speed a very simple matter.

The control shaft operating the phase shifter is provided with a pointer. When this pointer is stationary, irrespective of location, it indicates that the dynamometer speed corresponds exactly to the gearbox setting. This is all the speed measurement that is necessary. Chronographic checks have demonstrated that this system is very reliable, and that the maximum instantaneous variation from the set speed under steady load conditions is about 1 rpm.

Fig. 16 is a view looking down upon the gearbox with the cover removed to show the construction, and Fig. 17 shows the appearance of the assembly installed at the operator's table.

Torque Measurement. The method of mounting the dynamometer for weighing the torque reaction has already been described. The sensitivity of this mounting proved to be 0.01 ft-lb.

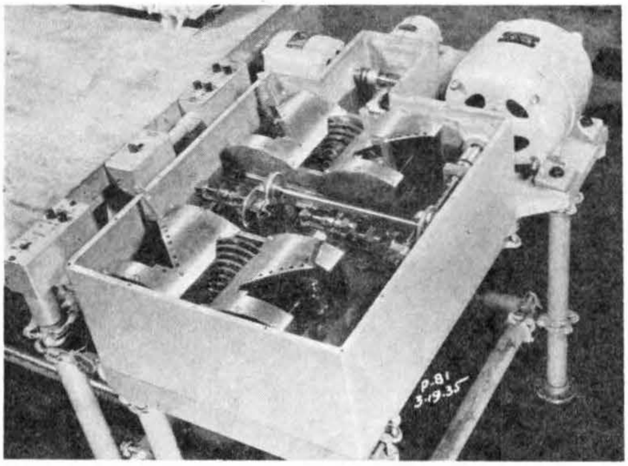

Fig. 16 Gearbox With Cover Removed

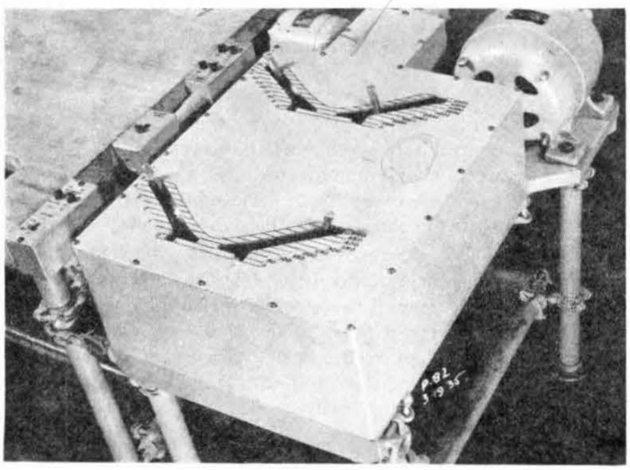

Fig. 17 The Gearbox Installation

In order to measure the torque accurately, two systems were installed, the lower and the upper weighing mechanisms. The lower weighing mechanism is manually operated and measures units of 100 ft-lb only, while the upper weighing mechanism is automatically balanced and weighs to the nearest 0.01 ft-lb, with a maximum of about 125 ft-lb. Together they have a capacity of 1200 ft-lb, which is sufficient for any condition of operation of the dynamometer.

Lower Weighing Mechanism. The lower weighing mechanism operates hydraulically. It consists of two ground and lapped pistons and cylinders mounted on the dynamometer base and working against knife-edges on the dynamometer, a smaller cylinder and piston of similar construction on the operator's table for applying the loads, a transmission line between them, and a pump for

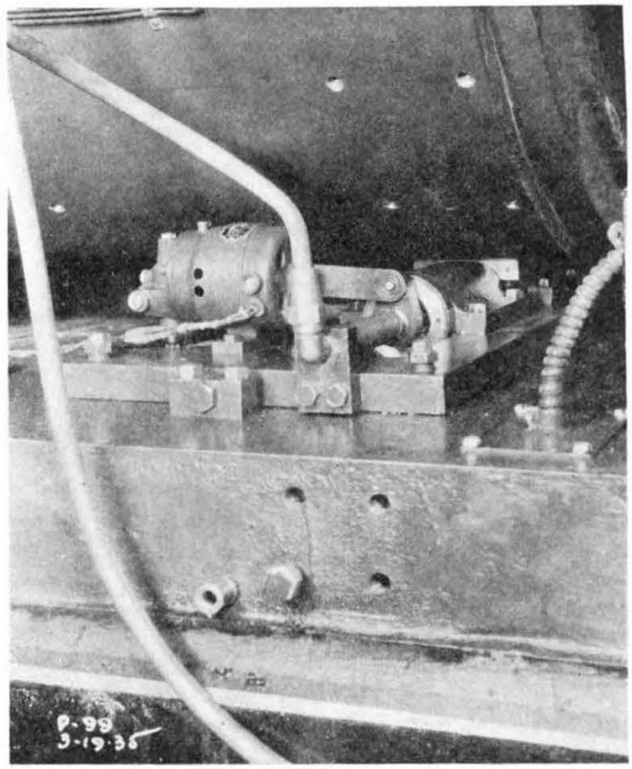

Fig. 18 Operating Portion of the Lower Weighing Mechanism Mounted on the Dynamometer

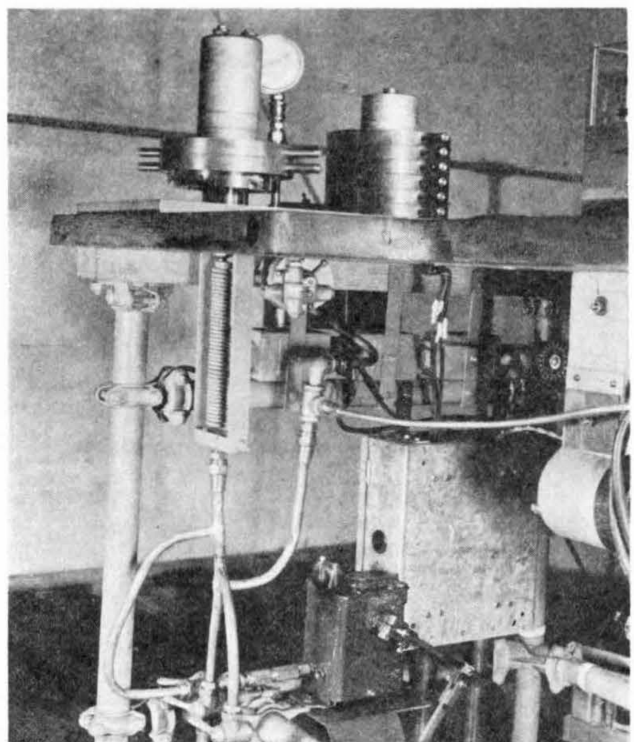

Fig. 19 Control Portion of the Lower Weighing Mechanism, Mounted on the Operator's Table

periodically supplying small quantities of oil to the system to take care of the leakage. The two sets of pistons and cylinders are required on the dynamometer to take care of both directions of rotation, but only one is in use at a time. The cylinders are all oscillated continuously by small motors, which eliminates wall friction and increases the sensitivity. The two dynamometer units are so accurately paired that there is no detectable difference in their readings. Although the pistons are about 1.25 in. in diameter, and the working clearances are the order of 0.0001 in., they can be interchanged in the cylinders.

Fig. 18 shows part of the dynamometer installation and Fig. 19 shows the parts that are on the operator's table. Note that the leakage supply pump is a stock high-pressure positive lubricator equipped with a motor drive which is operated from a push button conveniently located on the table. The stock of 100-ft-lb weights are to be seen on the table to the right of the piston and cylinder assembly. The oscillating motor is mounted close under the table top and is visible at the right of the flexible helix leading up to the cylinder.

Upper Weighing Mechanism. The upper weighing mechanism is very simple in operation and is mounted directly on top of the dynamometer. It consists of a calibrated weight which moves horizontally, normal to the axis of the dynamometer. It is driven by a precision screw which is carried in preloaded bearings to eliminate any back-lash. Therefore the revolutions of the screw measure the torque, and all that is necessary is to attach a revolution counter through a proper gear train to give the reading directly in foot-pounds. This is relayed to the operator's table with a pair of selsyns to increase the speed of testing. Fig. 20 shows the installation. The screw is driven by a reversing motor, which is controlled by sets of contacts between the

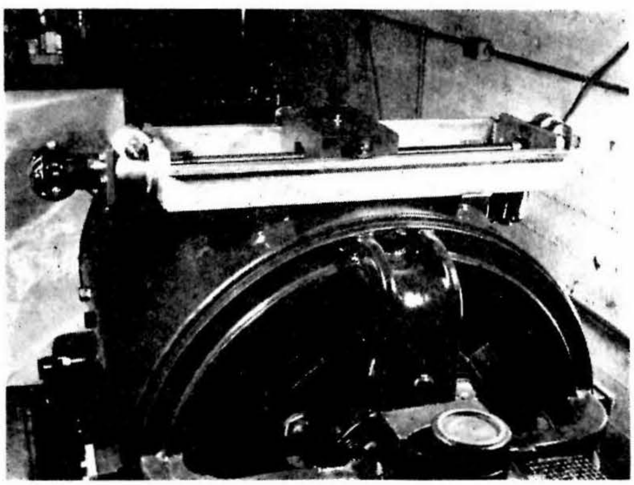

FIG. 20 THE UPPER WEIGHING MECHANISM

dynamometer frame and the base. The 0.003- to 0.004-in. freedom of oscillation permitted the dynamometer by the frame stops is sufficient to operate the contacts. Sparking and welding are prevented by use of vacuum-tube relay circuits, which also permit of an adjustable time delay which is used to prevent hunting. The same contact and relay system also operates solenoids of adjustable strength which apply small countertorques to the dynamometer frame. This, in combination with the time delay, has been successful in eliminating all hunting of the automatic balancing mechanism.

The calibration of both upper and lower systems is accomplished by hanging known weights directly on the dynamometer

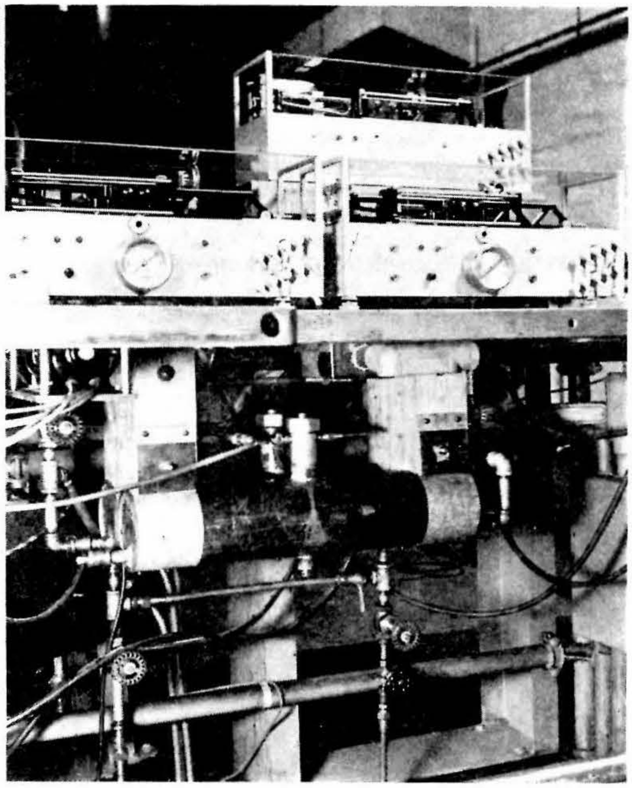

FIG. 21 OIL-OPERATED PRESSURE GAGES WITH OIL RESERVOIRS MOUNTED BENEATH

on knife-edges supplied for that purpose. The accuracy of the combined system considerably exceeds the 0.1 per cent limit originally set as the goal.

Head or Pressure Measurement. In working with hydraulic machinery, it is of course necessary to measure heads in terms of feet of the actual fluid used. However, since this varies considerably with temperature, the gages designed for the laboratory measure in pressure units instead, i.e., in pounds per square inch. In principle they are pressure-weighing scales, since they weigh the force the pressure exerts on a piston of known size. They are constructed with a single beam mounted on special scale ball bearings. On one end of the beam there is a weight pan and on the other a dashpot and two sets of contacts for operating the motor-driven rider that runs along the top of the beam. The force from the pressure piston is applied to the beam through another set of pivot bearings. This piston is ground and lapped and operates in a cylinder of the same construction, which is rotated by a small induction motor. The pressure is brought to the cylinder through another lapped fit at the opposite end.

Ten weights, each equivalent to 50 lb per sq in., are provided for the weight pan. Each one is carried in an individual frame and can be lowered onto or removed from the weight pan by a small lever on the front of the gage case. A small Bourdon gage of the conventional type serves to indicate the proper number of weights to apply to bring it within the self-balancing range of the rider. An extra weight is provided which normally rests on the pan. When this is lifted, the gage measures pressures from a hypothetical level 50 lb per sq in. below atmospheric pressure. To prevent air from being drawn into the system when reading negative pressures, a small oil reservoir is provided around the piston where it emerges from the cylinder.

The motor drive for the rider is mounted on the case instead of the beam. The rider itself is moved by a fine wire stretched along its length and located exactly in line with the pivot center of the beam. Thus, a force along the wire produces no torque on the beam and does not affect the balance. Clamped to the center of this wire is a split nut which runs on a precision screw, also mounted in preloaded bearings. This screw is driven by a small reversing induction motor running in oil under the case, which is controlled by the beam contacts through vacuum-tube relay circuits similar to those used on the upper weighing mechanism. The revolution counter driven by the screw gives the rider reading in hundredths of a pound per square inch. The inlet- and outlet-pressure gages are identical in construction and can be seen in the upper part of Fig. 21. Two balance lights and a cylinder-motor pilot light are seen on the front of the case. There are also switches for the manual operation of the rider and one which disconnects the contact relays from the beam motor and permits their use to control a motor-operated valve in case it is desirable to maintain a pressure at a fixed value.

To prevent deterioration of the lapped surfaces, the gages are operated with oil. Each one has a large oil reservoir directly

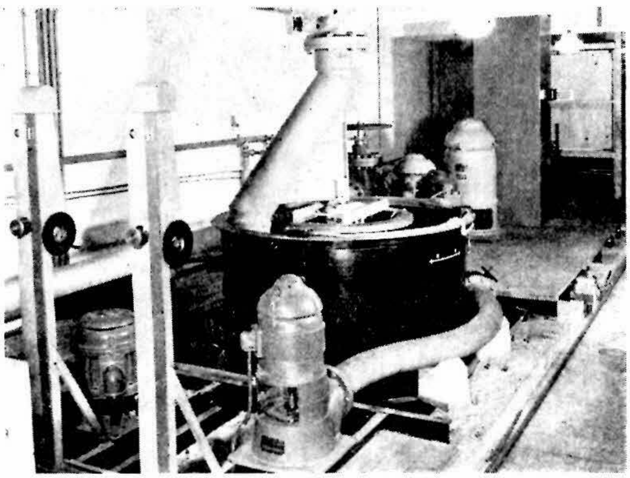

Fig. 22 Swing Spout and Distributing Chute on the Calibrating Tanks

beneath it as shown in Fig. 21. Any possibility of grit entering the cylinder is prevented by a fine-mesh strainer located in the turret on top of the reservoir. The reservoir is horizontal to permit a large volume change with a small level change in the oil, since the reading will be affected by the difference in density of the oil and water and the change in level. At the time of construction there was no precise knowledge of the rate of leakage of oil through the gage. Experience has now shown that the reservoirs have capacity for several years' operation per filling.

The primary calibration of the gages was simply the measurement of the piston and cylinder diameters and the lengths of the lever arms from the beam fulcrum to the piston pivot and to the weight-pan pivot, together with the weighing of the rider and the weights. This was also true for the primary calibration of the upper and lower torque-weighing mechanisms. The pressure gages were further checked by comparison with a Crosby deadweight gage tester, and an even more sensitive check was obtained by connecting them to the line of the lower weighing mechanism. The zero-reading balance is made by connecting them to an open riser filled with water to the level of the top of the gage cylinders.

Measurement of Rate of Flow, Primary Standard. The primary standard for measurement of rate of flow in the laboratory is the pair of volumetric calibrating or measuring tanks already described. They are used in conjunction with a swing spout and distributing chute so constructed that the flow suffers no disturbance when it is switched from one tank to the other. Fig. 4 shows the circuit employed.

Fig. 22 shows swing spout and distributing chute, with the

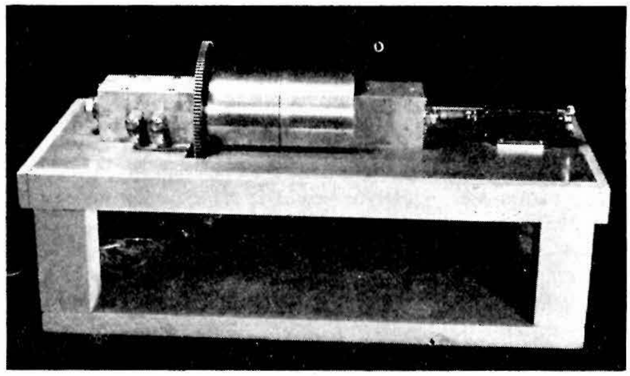

Fig. 23 Chronometer for Recording Time to Fill Calibrating Tanks

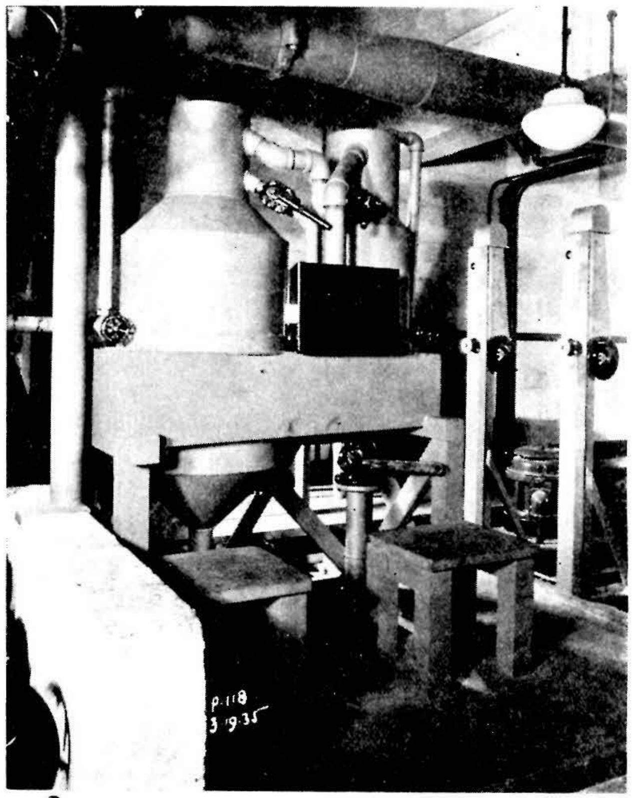

Fig. 24 Standardizing Pipettes and Measuring-Tank Point Gages

swing spout in position to discharge into the large calibrating tank. Note the use of the vane elbow at the entrance to the swing spout to insure even distribution and insensitivity to the position of the spout.

The common walls of the two calibrating tanks and the storage tank intersect at angles of 120 deg. The distributing chute is centered directly over their common intersection, and one third of it discharges into each tank. The swing spout is directly over the chute, and pivots about its center. It is driven by a constant-speed induction motor with integral gear reducer and electric brake. Limit switches on the rim of the chute permit it to travel only one third of a revolution before it is automatically stopped, i.e., the distance necessary to switch the flow from one tank to another. It is operated in either direction at will by push-buttons on the adjacent wall. The spout clears the knife-edged chute partitions by about 0.25 in., so a very clean cutoff is obtained. When the center of the spout is directly over the partition, a contact is made which actuates a special chronometer. Thus, the exact time of filling of a measuring tank is recorded. The time of passage across the partition is about 0.16 sec. Runs of less than 1 min are not taken. Therefore, inaccuracies due to dissimilarity of flow conditions in the spout when entering and leaving the tank must be of very small order.

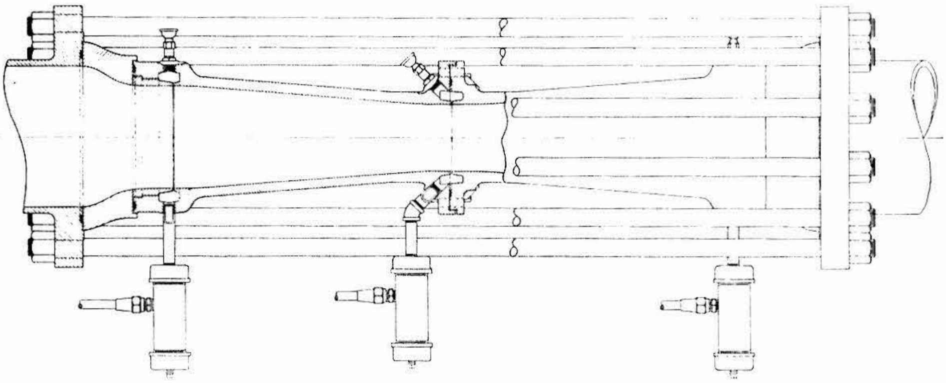
FIG. 26 CROSS SECTION OF THE VENTURI METERS

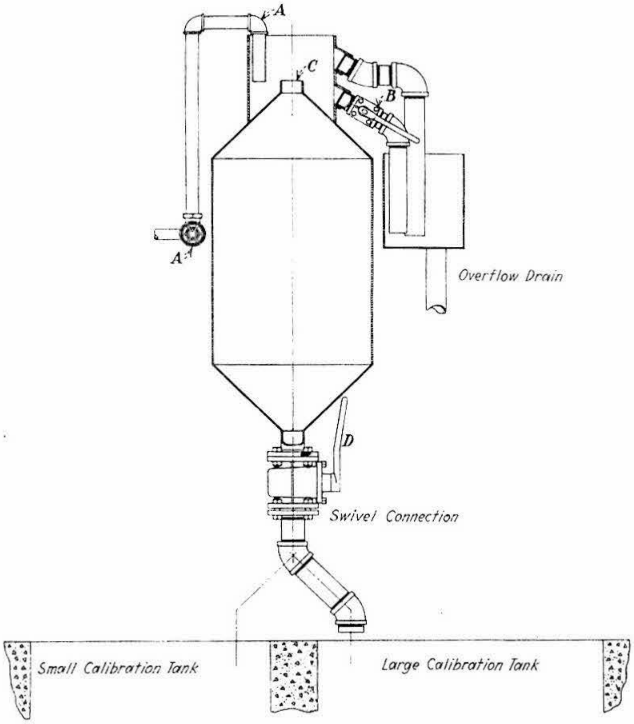

FIG. 25 CROSS SECTION OF THE STANDARDIZING PIPETTE

Chronometer. The special chronometer shown in Fig. 23 is used with these tanks. It is simply a revolution counter driven by a synchronous motor which is operated from the standard-frequency system. In use, the motor runs continuously but the counter is started and stopped by a pair of powerful magnetic clutches operated through surge circuits by the swing-spout contacts. The inertia of the counter mechanism is so low in comparison to the power of the clutches that the readings obtained are accurate to the nearest 0.001 sec.

Point Gages. The changes in level in the calibrating tanks are measured by point gages permanently mounted in each tank. These consist of a standard stainless-steel tape carrying a relatively heavy brass plummet which has a small platinum point protected by a bakelite ring. The tape is connected to the ungrounded side of the alternating-current lighting circuit through a neon glow lamp. As the point touches the water surface, the lamp lights, thus furnishing a sensitive method of locating the surface. The tape is read with a vernier, the smallest division of which is 0.001 ft. No difficulty is encountered in repeatedly duplicating readings to this precision. The installation is shown on the right in Fig. 24. The unused tape is wound on the reel seen on the side of the column. This is fastened with friction disks to the slow-motion shaft of a small commercial speed reducer. The knob seen in front is on the high-speed shaft and furnishes a micrometric slow motion for the tape.

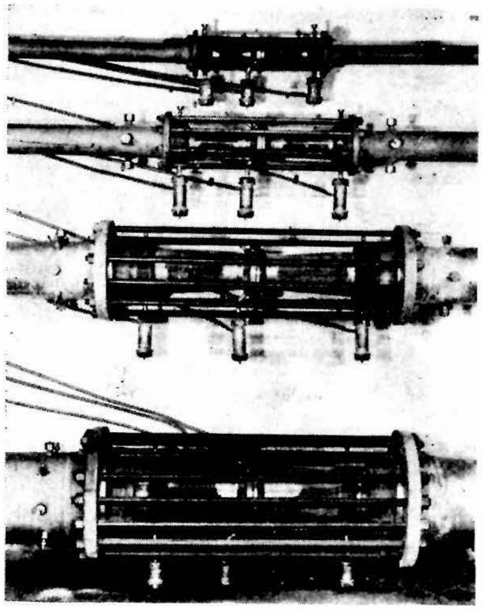
FIG. 27 THE INSTALLATION OF THE VENTURI METERS

Standardizing Pipettes. To standardize the measuring tanks a pair of pipettes were constructed. They are shown on the left in Fig. 24. Fig. 25 is a sectional elevation of one of the pipettes and shows the method of operation. The valves *D* and *B* are first closed. The pipette is then filled by admitting water through *A* into the filling ring, where it overflows crest *C* and enters the pipette body. When it is full, a slight additional rise causes water to run out of the overflow pipe. At this signal the operator closes valve *A*, opens *B* and drains the ring, thus leaving the pipette exactly full. Valve *D* is now opened and the pipette discharged into the measuring tank. A standard draining time of 5 min is allowed, after which the process is repeated and the next calibrating point secured. Since the small pipette holds about 3 cu ft, and the large one 10 cu ft, while the tanks hold

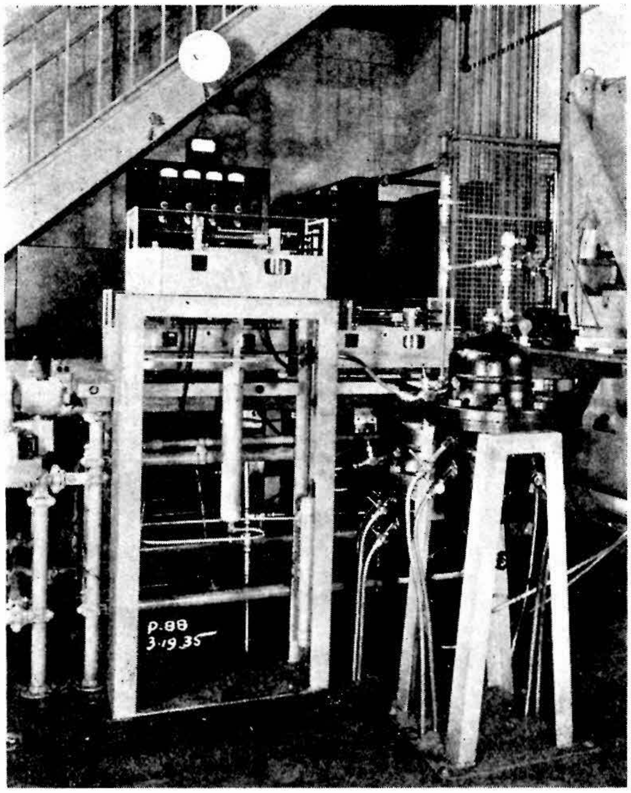

Fig. 28 Rear View of Venturi Manometer and Sediment Pots

300 and 1000 cu ft, respectively, it is possible to secure 100 points on each tank-calibrating curve. The pipettes themselves were standardized by weighing them both full and after a standard drain while they were suspended from one of the wind-tunnel balances. This balance was checked against standard weights and has a sensitivity of about a hundredth of a pound. A density determination of the water used was made at the temperature of the calibration.

Venturi Meters. Although always available for use, the measuring tanks require too much time to be convenient for normal testing. Therefore, a bank of four venturi tubes is provided as a secondary means of measuring rates of flow. These are graded in size so that each covers a range of only three to one, thus insuring a minimum of 3 in. of mercury differential pressure on the lowest rates permissible with each meter. Each meter is symmetrical and is provided with three piezometer rings, one on each end and one at the throat. Therefore, it is possible to measure flow in either direction by the proper selection of pressure connections. Fig. 26 shows a cross section of a typical tube and Fig. 27 shows the tubes installed. It will be seen in Fig. 26 that the piezometer opening is an annular slot. Its width is one tenth of its depth. This corresponds to accepted aerodynamic practice for accurate pressure measurements. Stuffing-box fittings are shown on the larger pipe just ahead of the venturi tubes in Fig. 27. These are for making velocity traverses with direction-finding tubes, which are being carried on in connection with a study of the tube coefficients.

Venturi Differential Manometer. The differential pressure from the venturi tubes varies from 3 to 30 in. of mercury. This is measured by the weighing-type differential mercury manometer shown in Fig. 28. Advantage was taken of the design developed for the pressure gage by using the mechanism in its entirety to weigh the low-pressure leg of the differential manometer. The piston and cylinder were omitted, the fulcrum point interchanged with the piston pivot point, and the manometer tube was suspended from the previous location of the fulcrum. The suspended

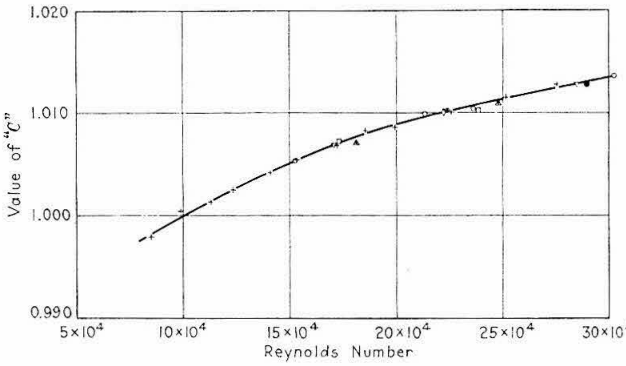

Fig. 29 Calibration Curve for the 12-In. Venturi Meter

manometer tube is connected to the other leg by a horizontal loop of thin-walled tubing about 3 ft long. On the beam, the contacts have a total clearance of about 0.003 in., and the manometer suspension point has about one tenth their lever arm, thus giving it a motion during weighing of about 0.0003 in. The force required to deflect the connecting tubes this minute amount has been found to be negligible. The manometer proper is constructed entirely of stainless steel. The sensitivity of the system is about 0.0006 in. of mercury.

Sediment Pots. Interposed between the venturi tube and the differential manometer are two sediment pots, one for each leg. They serve as headers as well, for all four throat connections come to one, and all eight end connections come to the other. Each line is provided with a ground cock, so that by proper selection any meter can be connected to the manometer to measure flow in either direction. These sediment pots are shown on the right-hand side of Fig. 28. It will be seen that they are in two parts, connected with a flange joint. The lower flange also serves to support a separating plate, on the bottom side of which are 12 short tubes, about 1.25 in. diameter, brazed to corresponding holes in the plate. Fastened over each tube and suspended from it is a very thin rubber bag. Upon assembly, the bags in the throat pot are collapsed with the lower half full of water, while those in the end-connection pot are nearly filled to capacity, although care is taken to insure that there is no distention of the rubber. The upper halves of the pots are then put in place and the manometer side of the system filled with distilled, deaerated water. Thus, the manometer operates in a closed system with no chance for dirt to enter it and collect in the mercury surfaces. However, since the combined volume of the rubber bags in each pot is considerably greater than the total volume of mercury displaced, no pressure difference can exist across the seal.

Venturi Calibration. Each venturi tube is calibrated by the measuring tanks in the manner described previously. Since it is possible for the water temperature in the laboratory to vary considerably under different testing conditions, the meter coefficients are plotted against Reynolds numbers instead of rate of flow. One of the typical calibration curves is shown in Fig. 29. The meter calibration is very constant, as shown by calibration runs taken at various times during the work. This is not surprising, since the meters are constructed entirely of bronze, and the approach lines are galvanized.

Operators' Table. From the foregoing description it is evident that the heart of the laboratory is the operator's table. Two views of this are seen in Figs. 30 and 31. The former shows the relative location of the different measuring instruments and controls. The latter shows the convenience of the operator's position with reference to such equipment as the main control board, the standard-frequency cabinet, and the thyratron installation.

It has been seen that the dynamometer, the pressure gages, and the venturi manometer are all self-balancing, and are operated

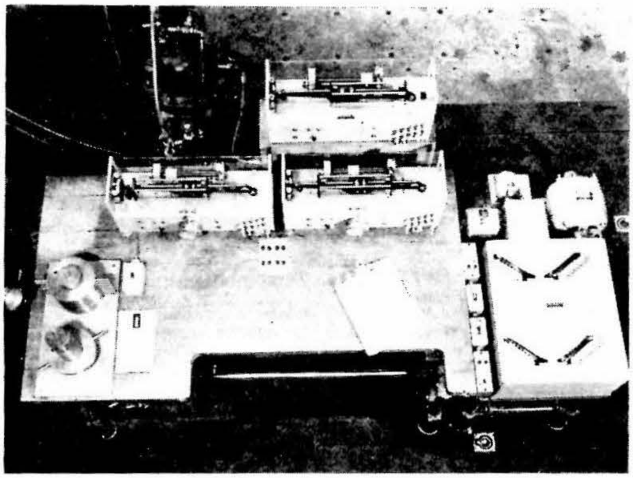

FIG. 30 TOP VIEW OF OPERATOR'S TABLE

by small motors. In order to secure simultaneous readings and to speed up the work, all of these balancing motors operate from a common circuit, the control switch of which is placed in a location convenient to the operator's hand. When making a run, he therefore simply watches the pilot lights from these instruments and when they all indicate a balance he opens this master switch and stops all of the balance motors. He then makes his adjustments for the next desired condition, and, while the new flow is coming to equilibrium, he records the previous measurements, as read on the various revolution counters. This accomplished, the switch is again closed, and in a few seconds all of the instruments are again indicating a balance. During all this time the speed-control system has been holding the dynamometer speed absolutely constant.

Overall Accuracy of Measurements. Table 1 gives a summary of the accuracy of measurements for the different principal readings. It shows that even when all of the available sensitivity is not employed each principal quantity is measured with an accuracy of better than 0.1 per cent, the goal originally set. The laboratory personnel feel, however, that for normal work a combined figure of accuracy of 0.1 per cent is about what is justified, because of minor instabilities in the flow itself which tend to lessen the precision. On the other hand, on several occasions the staff has tried to blame unexpected apparent irregularities of performance of individual test machines on the testing

TABLE 1 ACCURACY OF PRINCIPAL LABORATORY READINGS

Reading	Range	Sensitivity: Maximum	Sensitivity: Per cent of average reading	Smallest normal reading: Reading	Smallest normal reading: Per cent of average reading
Speed	1000 to 5000 rpm	1 rpm[a]	0.033	1 rpm[a]	0.033
Torque	0 to 1200 ft-lb	0.01 ft-lb	0.0025	0.1 ft-lb	0.025
Pressure	−15 to 550 lb per sq in.	0.01 lb per sq in.	0.007	0.1 lb per sq in.	0.067
Rate of flow	3 to 30 in. Hg	0.0006 in. Hg	0.002	0.006 in. Hg	0.02

[a] Fluctuation about mean value—not deviation from reading.

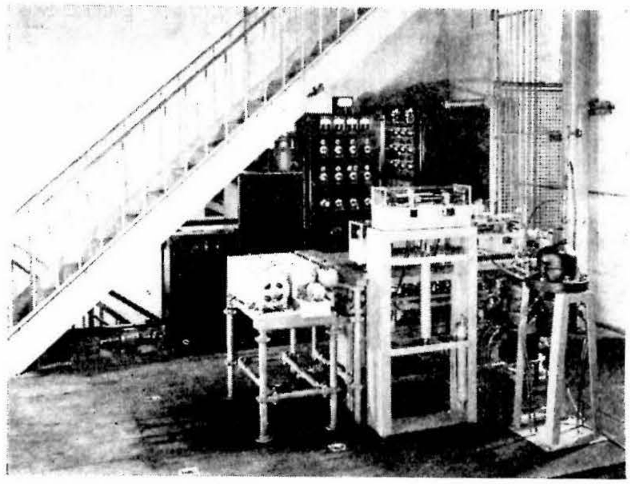

FIG. 31 REAR VIEW OF OPERATOR'S TABLE

equipment, but in each case rigorous investigation has absolved the instruments from suspicion of error and has proved that the irregular performance was actually a fixed and duplicable characteristic of the machine in question. Therefore, they are now firm in their conviction that the claim of 0.1 per cent accuracy is amply justified.

Necessary Modifications to Calculation Technique. To take advantage of the experimental accuracy available, certain modifications of the usual calculating methods have been found to be necessary. On the other hand, a great time and labor saving has been achieved by the elimination of the necessity of correcting the other readings for speed variations.

The fundamental units which measure the performance of any hydraulic machine are the head in feet of the fluid flowing and rate of flow in cubic feet per second of the fluid flowing. These are the units employed by the laboratory and the readings taken must be reduced to these terms.

The pressure gages measure the head in pounds per square inch. These readings are readily converted to head of actual fluid by the use of a conversion factor read from a chart on which is plotted its variation with temperature. However, since the piezometer rings are several pipe diameters away from the machine, and since the velocities may be as high as 40 fps, it is necessary to make a correction for pipe friction. The friction coefficient used is that for normal flow, and any additional friction existing due to nonuniform velocity distribution is charged against the machine.

The procedure for the rate-of-flow measurements is somewhat more complex. The reading of the differential manometer actually is a weight of mercury instead of a height. This helps to eliminate a correction for mercury temperature. By means of a factor from another chart, this reading is converted into feet of water at the temperature of the testing circuit. From this figure and the temperature, the Reynolds number of the venturi tube in use is graphically determined. Reference to the curve of meter coefficient vs. Reynolds' number gives the correct meter coefficient, and from this and the corrected differential reading the rate of flow is calculated.

The values of torque are correct as read. However, in order to make all the laboratory results comparable, water horsepowers are calculated from the head and rate-of-flow figures by the use of the density of water at standard temperature, that is, 68 F. Therefore, in calculating dynamometer horsepower, it is necessary to reduce the torque figure to the same basis by multiplying it by the ratio of the standard water density to the actual density. The overall efficiency calculations are not affected by this reduction.

Review of Laboratory Facilities. It has been stated that an attempt was made to secure the maximum versatility of laboratory equipment compatible with the known objective. Up to the present time the laboratory has used this equipment only in the study of the problems arising in connection with the design of pumping plants for the Colorado River aqueduct. However, it is obvious that its possibilities of application extend into much wider fields. There are some obvious limitations. High rates of flow at low heads offer difficulties because the line velocities have been kept rather high with correspondingly appreciable friction losses. The dynamometer is essentially a high-speed machine, and below about 2400 rpm the maximum power available decreases directly with speed. Although the gearbox can be set to control any speed below its theoretical maximum of 5555 rpm, it is not feasible to use it below about 1000 rpm because of the increasing load on the gear teeth at the lower rates. Only machines that can operate with horizontal shafts have been provided for, and of course work with open conduits belongs in the hydraulic-structures laboratory rather than in the laboratory herein described. The following classes of problems, however, are within the scope of the equipment, and represent the fields of investigation in which the laboratory will be employed after the completion of its original objectives:

(*a*) Pumps or turbines up to 12 cfs maximum capacity, 700 ft maximum head, 5000 rpm maximum speed, and 400 hp maximum power.

(*b*) Explorations of internal-flow conditions in hydraulic machinery.

(*c*) Valves, conduits, or fittings investigations at high velocities.

(*d*) Similar investigations involving noncorrosive liquids other than water, since system is closed and isolated.

(*e*) In general, problems requiring flows at high Reynolds, numbers and precision of measurements.

Acknowledgments

The primary responsibility for the development of the laboratory and its equipment has rested on the shoulders of the members of the supervising committee named at the beginning of this paper. In addition, special acknowledgment is due to the following men, who have contributed much to the design and construction. Dr. Frank Wattendorf was in charge of the operative staff during the period of construction and initiation of testing. Ralph M. Watson has held the same position for the latter half of the laboratory's existence. Dr. George Wislicenus and Dr. R. C. Binder have carried out much of the detailed design of the mechanical equipment and instruments. Emmet Irwin was responsible for the main electrical design, and E. E. Simmons and H. L. Levinton have both designed and constructed most of the special vacuum-tube circuits. Finally, the successful operation of the special precision instruments and control equipment has been due in a large measure to the exquisite workmanship of Fred C. Henson, in whose local instrument shop most of them were constructed.